Inhomogeneous phases of dense nuclear matter

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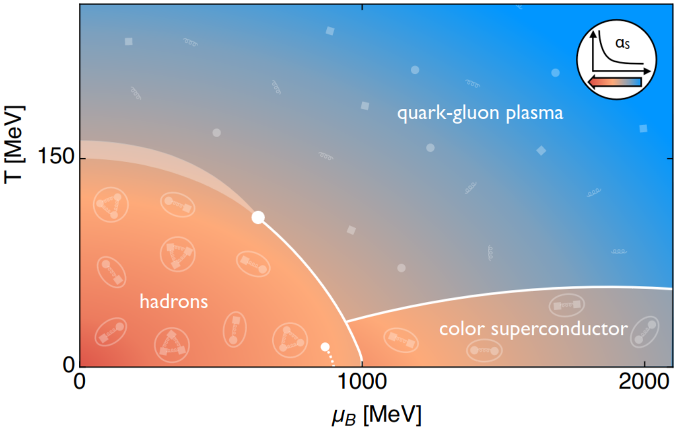
18^{th} August, 2026 SEWM Helsinki

In collaboration with Gastão Krein & Randall Pradinett

[PhysRevD-L071503] & [PhysRevD-113-9-094028]

QCD Phase Structure

$$\mathcal{L} = \frac{1}{4} F^a_{\mu\nu} F^a_{\mu\nu} + \bar{\psi}(\not{D} + m_q)\psi$$



↪ Plot by Fabian Rennecke

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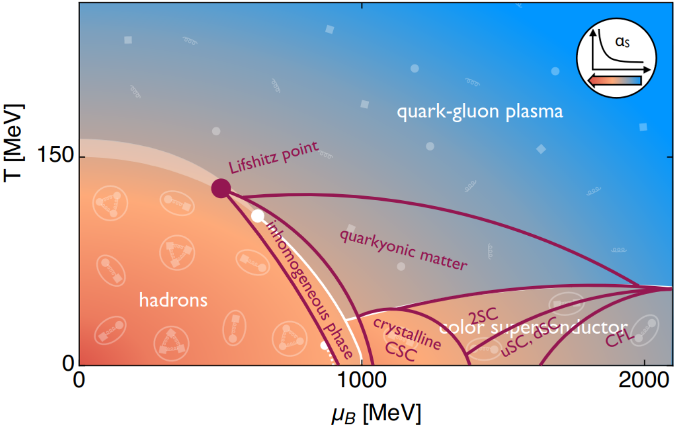
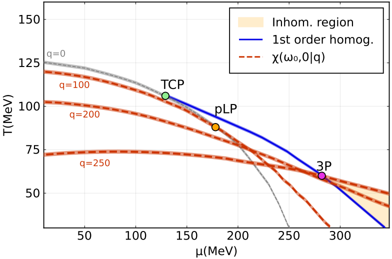
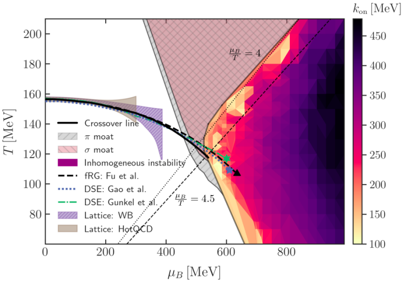


 ↪ Plot by Fabian Rennecke

Some QCD results





- DSE based calculation

  [**TFM**, J. Bernhardt, M. Buballa, C. Fischer, Phys.Rev.D 111 (2025) 7, 074030]

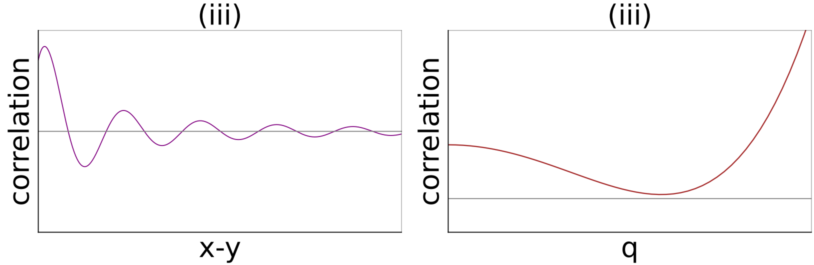
- FRG based calculation

  [J. Pawlowski, F. Rennecke, F. Sattler, arXiv: 2512.20510]

Correlation Functions

$$\langle \psi(x)^\dagger \hat{\mathcal{O}} \psi(x)\ \psi(y)^\dagger \hat{\mathcal{O}} \psi(y) \rangle = f(x - y)$$

- There is something "in between", however, the moat regime
- The phase is homogeneous, but it's correlation function...



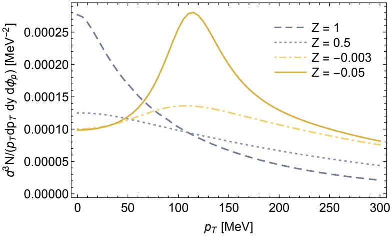
Moat signatures

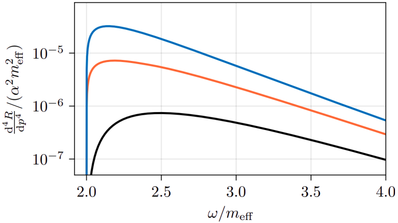
- Particles produced at finite momentum

  [Phys.Rev.Lett. 127 (2021) 15, 152302]

- Increased dilepton production

  [Phys.Rev.Lett. 135 (2025) 10, 101904]





What about dense nuclear matter?

- Migdal's work in the 70's about π condensation
- "The Possibility of a liquid crystal phase in nuclear matter"
  PLB by Migdal and P. Watson
- From the classic 1997 Review by Serot & Walecka:

2. In nuclear matter in the RRPA, poles appear in the polarization propagator at zero frequency $q_0 = 0$ and finite wavenumber $|\mathbf{q}| \neq 0$; the value of this wavenumber is a few times the nucleon mass in QHD–I.[57,84–86,91] Such poles imply an instability of the system against density fluctuations of the corresponding wavelength. There are several possible interpretations of these results:

   (a) The RRPA for the propagators is inadequate.

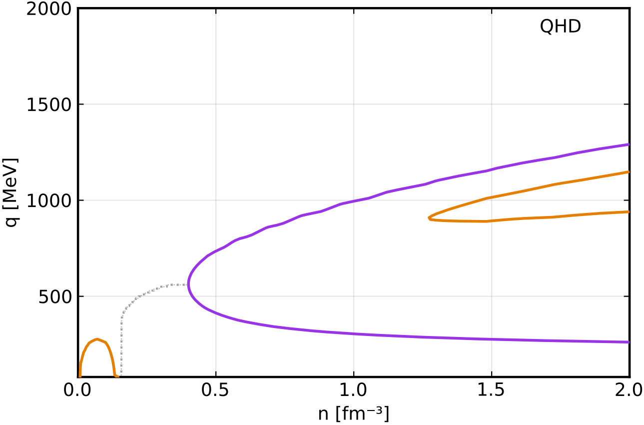
   (b) Vertex modifications are important. (Phenomenological form factors affect the numerical results significantly.[84])

   (c) The composite structure of the baryon must be taken into account before one reaches distance scales where these poles develop.

   (d) The instability is real.

Zeros of the SDF in QHD

$$\epsilon(n_b, \vec{q}) = \det\left(\sim\!\bullet\!\sim^{-1} \right) = \epsilon_L(n_b, \vec{q})\epsilon_T(n_b, \vec{q})^2$$



[Reproducing K. Lim, C. Horowitz Nucl.Phys.A 501 (1989) 729-750]

Quark-Meson-Coupling model (QMC)

$$
\begin{aligned}
(i\partial\!\!\!/ - m_q + g_\sigma^q \sigma - g_\omega^q \gamma^0 \omega_0)\psi = 0 \\
i\gamma \cdot \hat{r}\psi(R) = -\psi(R)
\end{aligned}
$$

- Quarks are confined in spherical bags
- Quarks interact with quarks via meson exchange

$$
\psi_m(\vec{r}) = \mathcal{N} \begin{pmatrix} j_0\left(xr/R\right) \\ i\beta_q \vec{\sigma} \cdot \hat{r} j_1\left(xr/R\right) \end{pmatrix} \frac{\chi_m}{\sqrt{4\pi}}
$$

- Use this to calculate the energy of a stationary bag, the baryon mass $M^\star(n_s)$

Quark-Meson-Coupling model (QMC)

- So if I take this result for $M^\star$ and put it into the baryon propagator

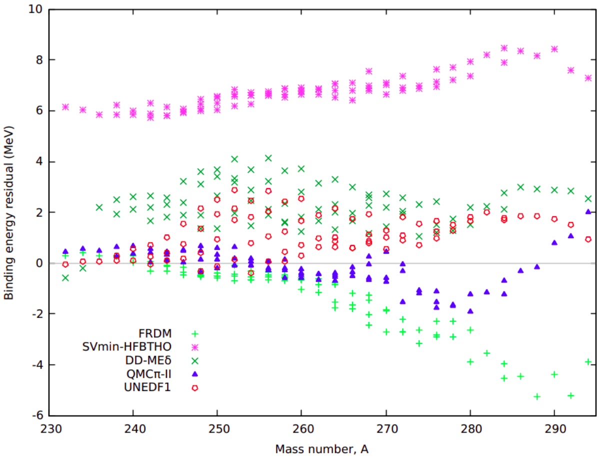
$$G_F(k) = \frac{\not{k} + M^*}{k^2 - M^{*2} + i\epsilon}$$
$$G_D(k) = 2\pi i(\not{k} + M^*)\delta\big(k^2 - M^{*2}\big)\,\eta(k_0)$$

  I can do nuclear many-body physics

- I can also obtain the effective coupling in MF by

$$\Gamma(n_s) \propto \frac{\partial M^\star}{\partial n_s}$$

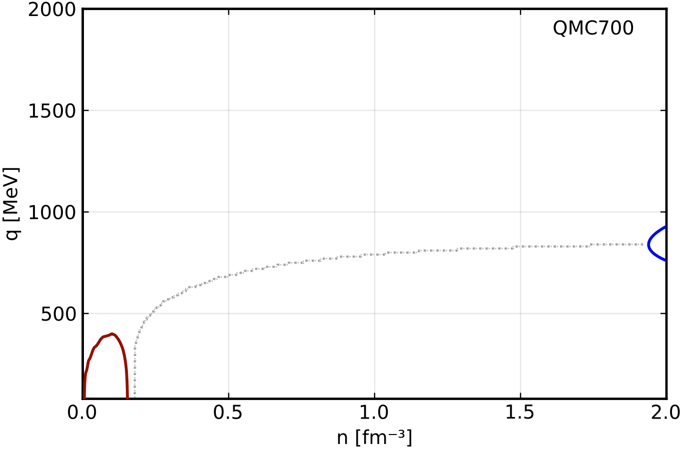
Quark-Meson-Coupling model (QMC)



- Quark–Meson-Coupling (QMC) model for **finite nuclei**, nuclear matter and beyond [P.A.M. Guichon, J. Stone, A.W. Thomas, Prog.Part.Nucl.Phys. 100 (2018) 262-297]
- The role of baryon structure in **neutron stars** [T.F. Motta, A.W. Thomas, Mod.Phys.Lett.A 37 (2022)]

Quark-Meson-Coupling model (QMC)

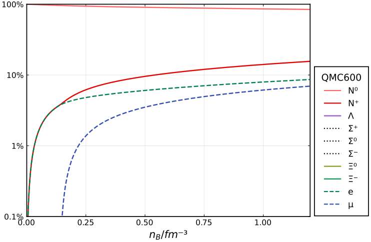
$$\epsilon(n_b, \vec{q}) = \det\left(\text{\textasciitilde}\bullet\text{\textasciitilde}^{-1} \right) = \epsilon_L(n_b, \vec{q})\epsilon_T(n_b, \vec{q})^2$$

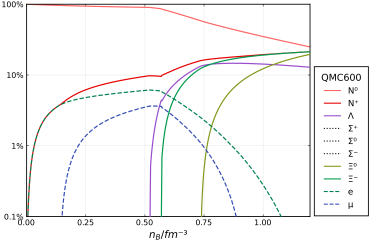


Quark-Meson-Coupling model (QMC)

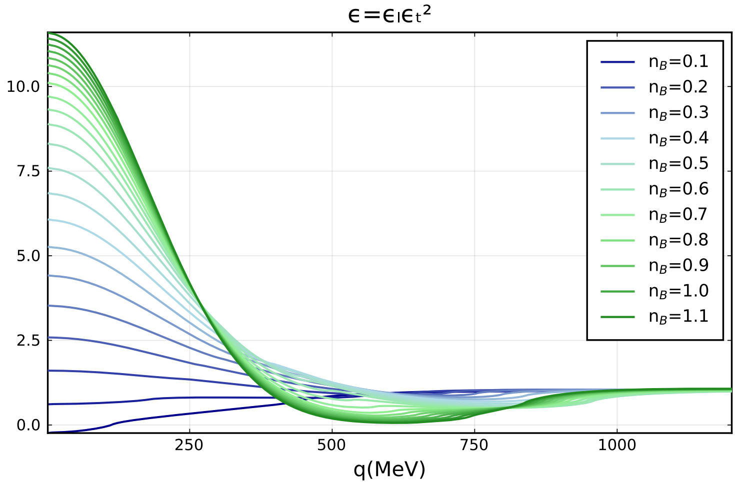
- We can write the energy density of INM as

$$\mathcal{E}(\{n_b\}) = \sum\!\!\!\!\!\!\!\int_{\vec{k}} \sqrt{k^2 + M_b^{\star 2}} +$$  $$+$$  ,



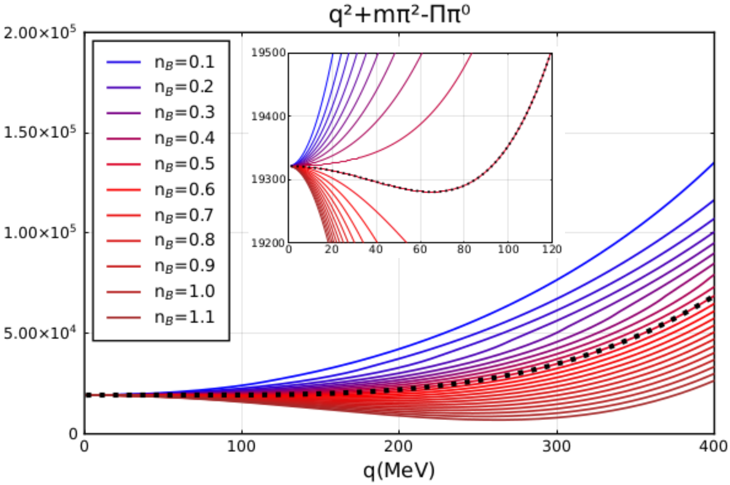


- The stability analysis of the **isoscalar** channels

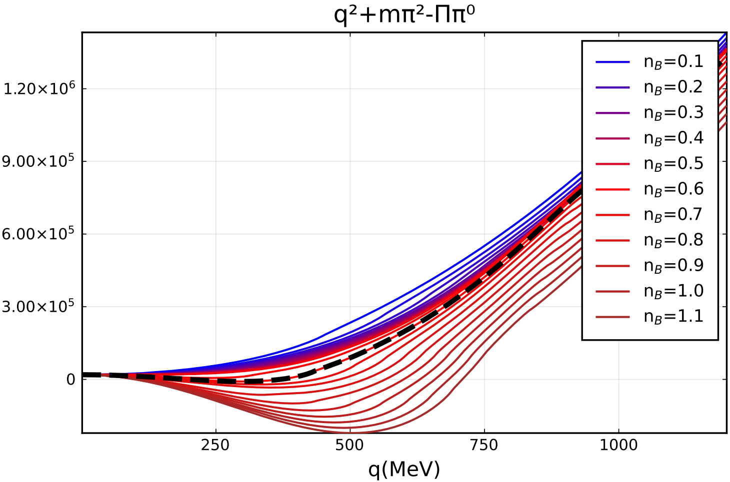


Nucleons only β-equilibrium

- Looking at the pions specifically



- Again... Looking at the pions specifically



Conclusions

- Moat regimes are most likely present in dense nuclear matter
- No instability is present with nucleons only
- Instabilities show up for high density hyperon rich matter

backup

Nuclear Matter (RMF)

- Take a model, any model

$$\mathcal{L} = \bar{\psi}_b(i\partial\!\!\!/ - M_b)\psi_b + g_\sigma^b\bar{\psi}_b\sigma\psi_b - g_\omega^b\bar{\psi}_b\omega\!\!\!/\psi_b$$
$$- g_\rho^b\bar{\psi}_b\rho\!\!\!/_a\tau_a\psi_b - \frac{g_A}{2f_\pi}\bar{\psi}_b\gamma_5\partial\!\!\!/\pi_a\tau_a\psi_b + \mathcal{L}_{\sigma\,\omega\,\rho\,\pi},$$

- Essentially what we want to do is

$$\Omega[n_s(\vec{x}), n_{ps}(\vec{x}), n_b(\vec{x}), \ldots] \qquad \text{around} \qquad n(\vec{x}) \to \bar{n} + \delta n(\vec{x})$$

  Which we can write as

$$\Omega[n(x)] \approx \Omega[\bar{n}] + \delta\Omega[\bar{n},\, \delta n(\vec{x})].$$

RRPA

- So the key piece of the analysis is

$$\delta\Omega[\bar{n},\, \delta n(\vec{x})] = \int_{\vec{q}} |\delta n(\vec{q})|^2\, D_\phi^{-1}(q_0 = 0, \vec{q})$$

- So the key piece of the key piece of the analysis really is D_ϕ^{-1}

- Whith the added caveat that

$$= \begin{pmatrix} \Pi_s & \Pi_\mu \\ \Pi_\nu & \Pi_{\mu\nu} \end{pmatrix}.$$

Quark-Meson-Coupling model (QMC)